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Campos

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(54) **OPTICAL COMMUNICATION SYSTEMS AND METHODS**

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H04B 10/2575	(2013.01)
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USPC 398/59, 66, 67, 70–72, 188, 183, 185, 398/186, 154, 155

See application file for complete search history.

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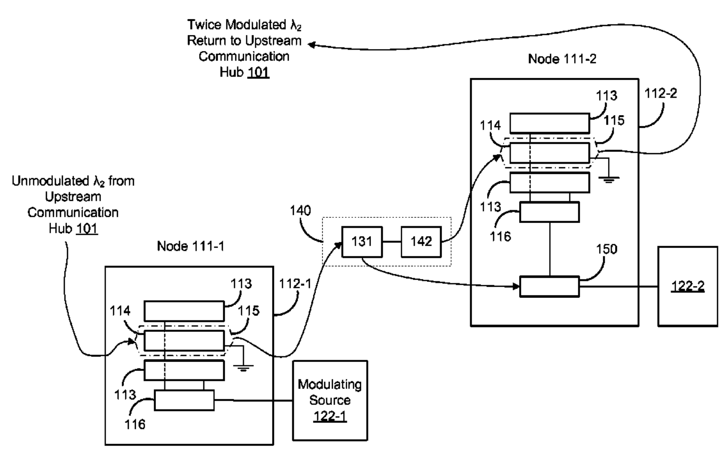
(74) *Attorney, Agent, or Firm* — Duft Bornsen & Fettig LLP

(57) **ABSTRACT**

Systems and methods presented herein provide for optical communications. In one embodiment, a communication system includes a plurality of communication nodes and a communication hub. A bundle of optical fibers optically links the nodes to the communication hub. The communication hub includes a laser operable to propagate unmodulated laser light to a first node along a first of the optical fibers in the bundle. The first node is operable to modulate the laser light with a first modulating signal source, and to propagate the modulated laser light to a second node. The second node is communicatively coupled to a second modulating signal source and to the first node. The second node is operable to optically combine upstream communications from the second modulating signal source with the modulated laser light from the first node, and to propagate the modulated laser light with the upstream communications to the communication hub at a same carrier wavelength.

12 Claims, 13 Drawing Sheets



(51) **Int. Cl.**
H04B 10/2587 (2013.01)
H04L 27/34 (2006.01)

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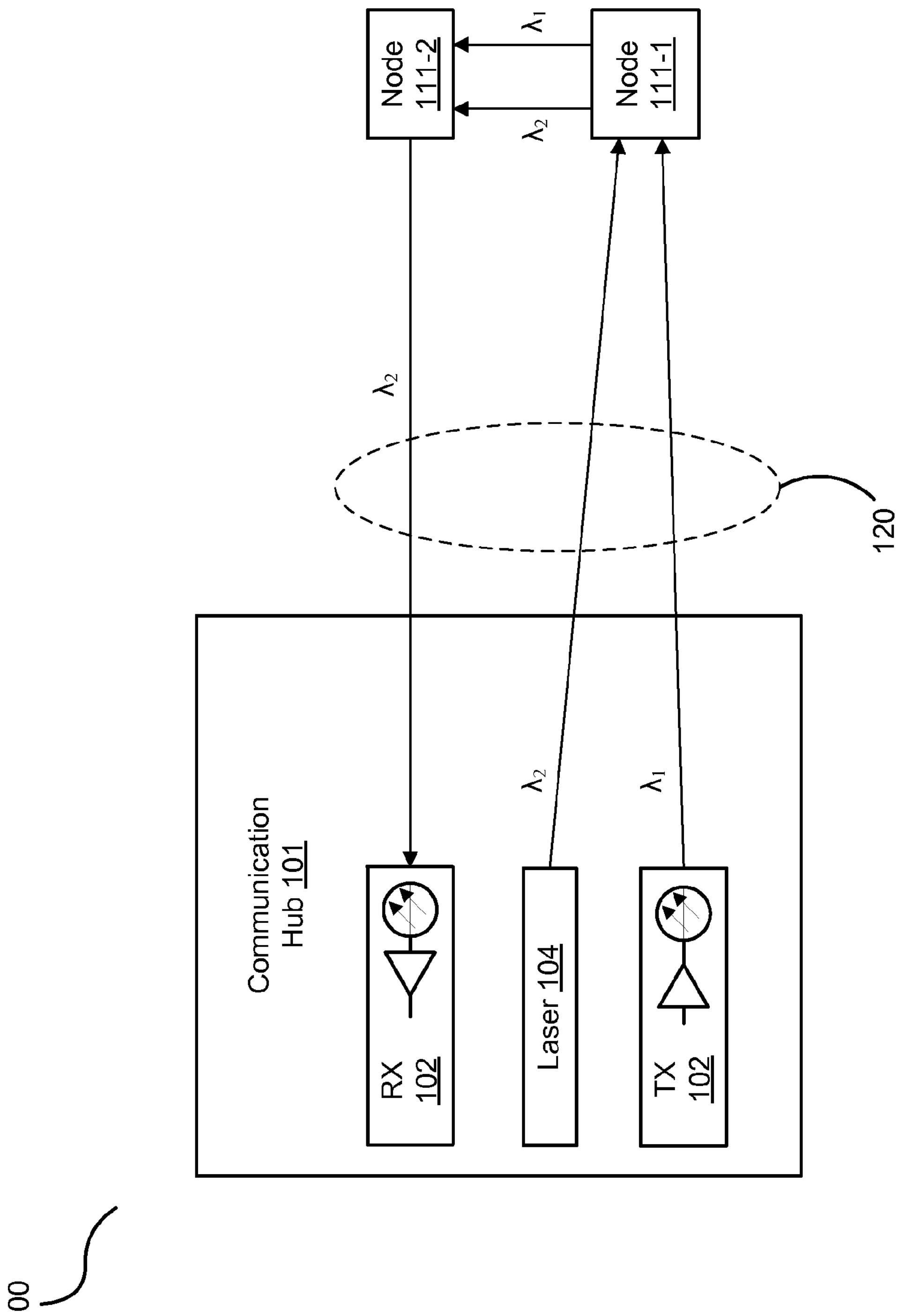

Node
111-2
Node
111-1
λ_1
λ_2
λ_2
120
Communication
Hub 101
λ_2
λ_1
RX
102
Laser 104
TX
102
100

FIG. 1

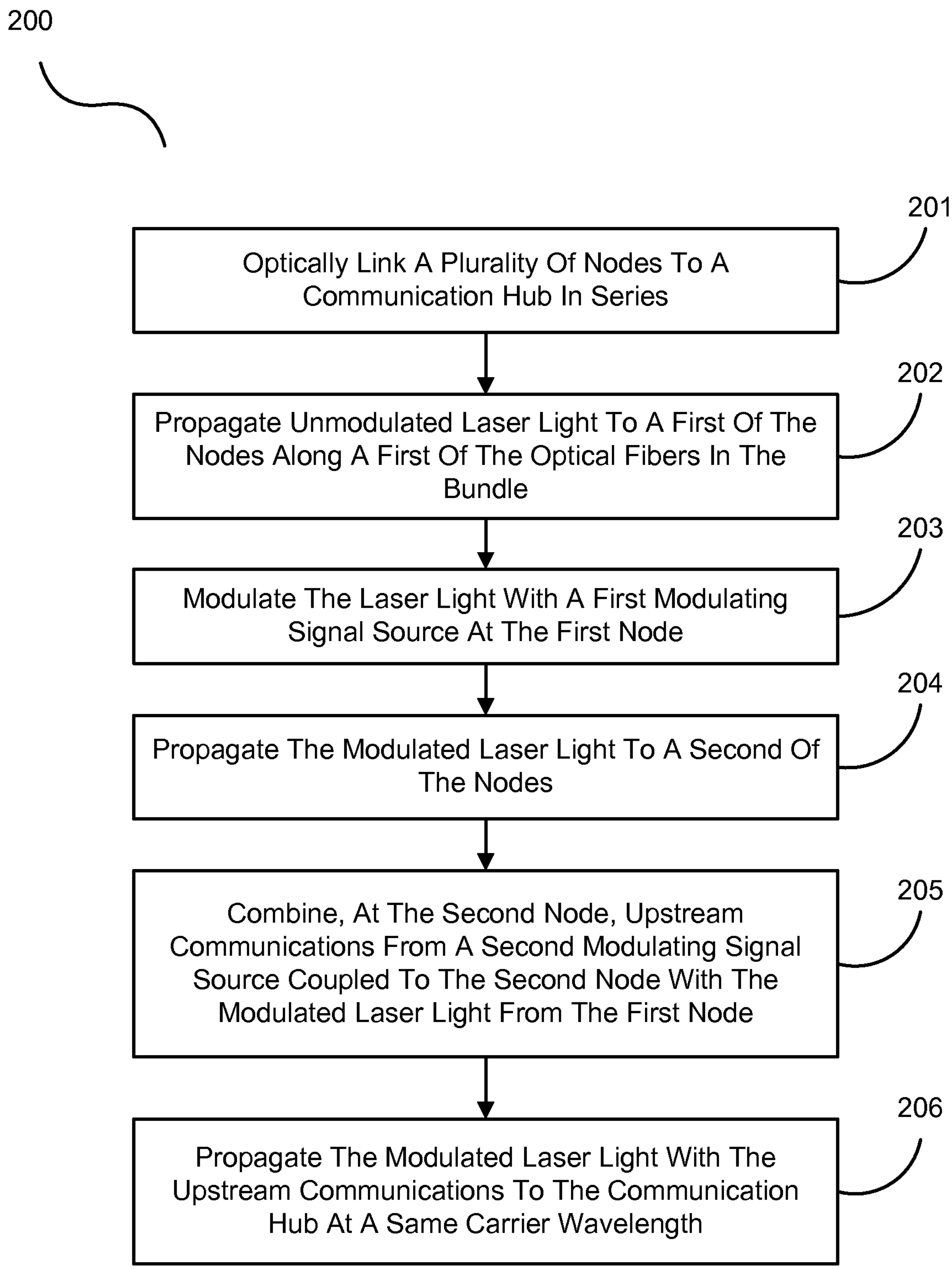

200
201
Optically Link A Plurality Of Nodes To A Communication Hub In Series
202
Propagate Unmodulated Laser Light To A First Of The Nodes Along A First Of The Optical Fibers In The Bundle
203
Modulate The Laser Light With A First Modulating Signal Source At The First Node
204
Propagate The Modulated Laser Light To A Second Of The Nodes
205
Combine, At The Second Node, Upstream Communications From A Second Modulating Signal Source Coupled To The Second Node With The Modulated Laser Light From The First Node
206
Propagate The Modulated Laser Light With The Upstream Communications To The Communication Hub At A Same Carrier Wavelength

FIG. 2

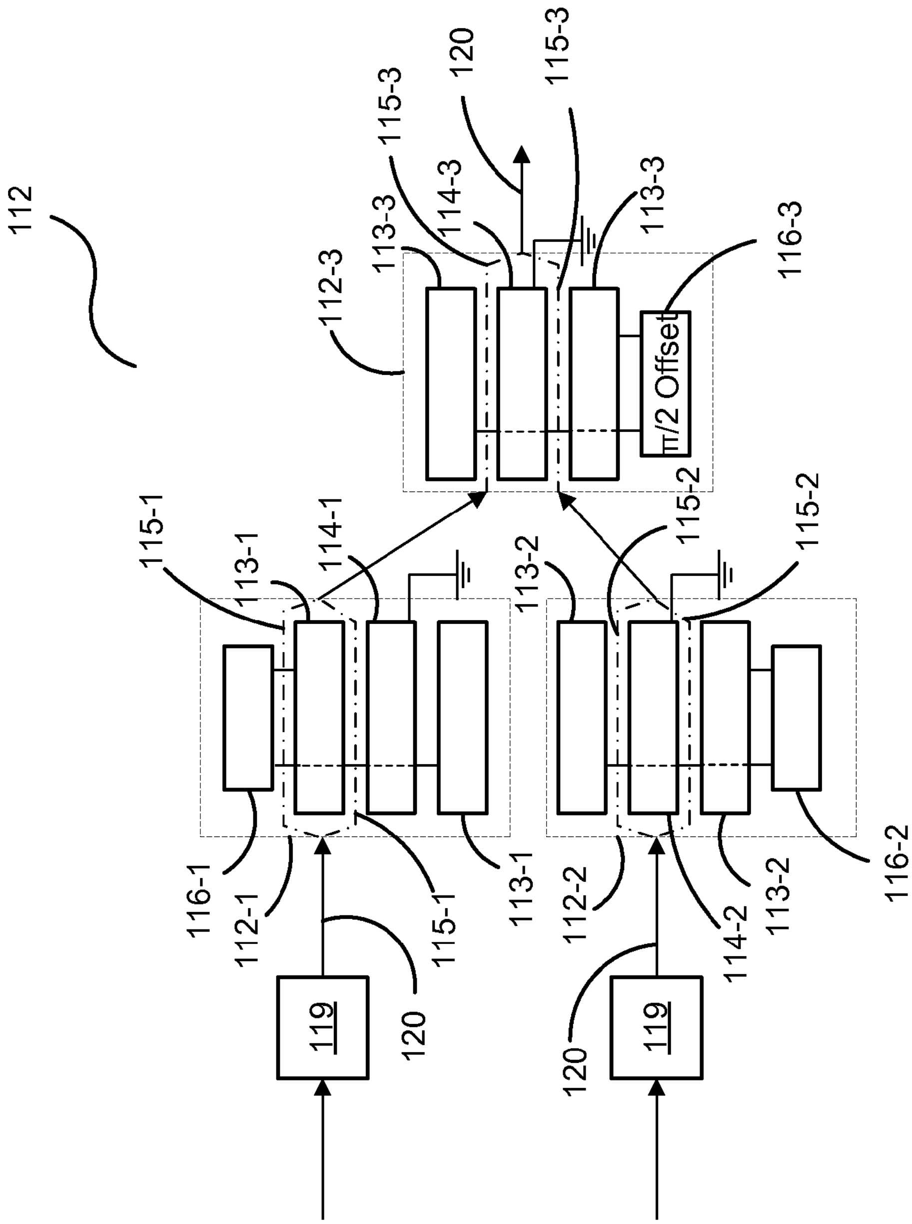

112
112-1
112-2
112-3
113-1
113-2
113-3
114-1
114-2
114-3
115-1
115-2
115-3
116-1
116-2
116-3
119
120
π/2 Offset

FIG. 3

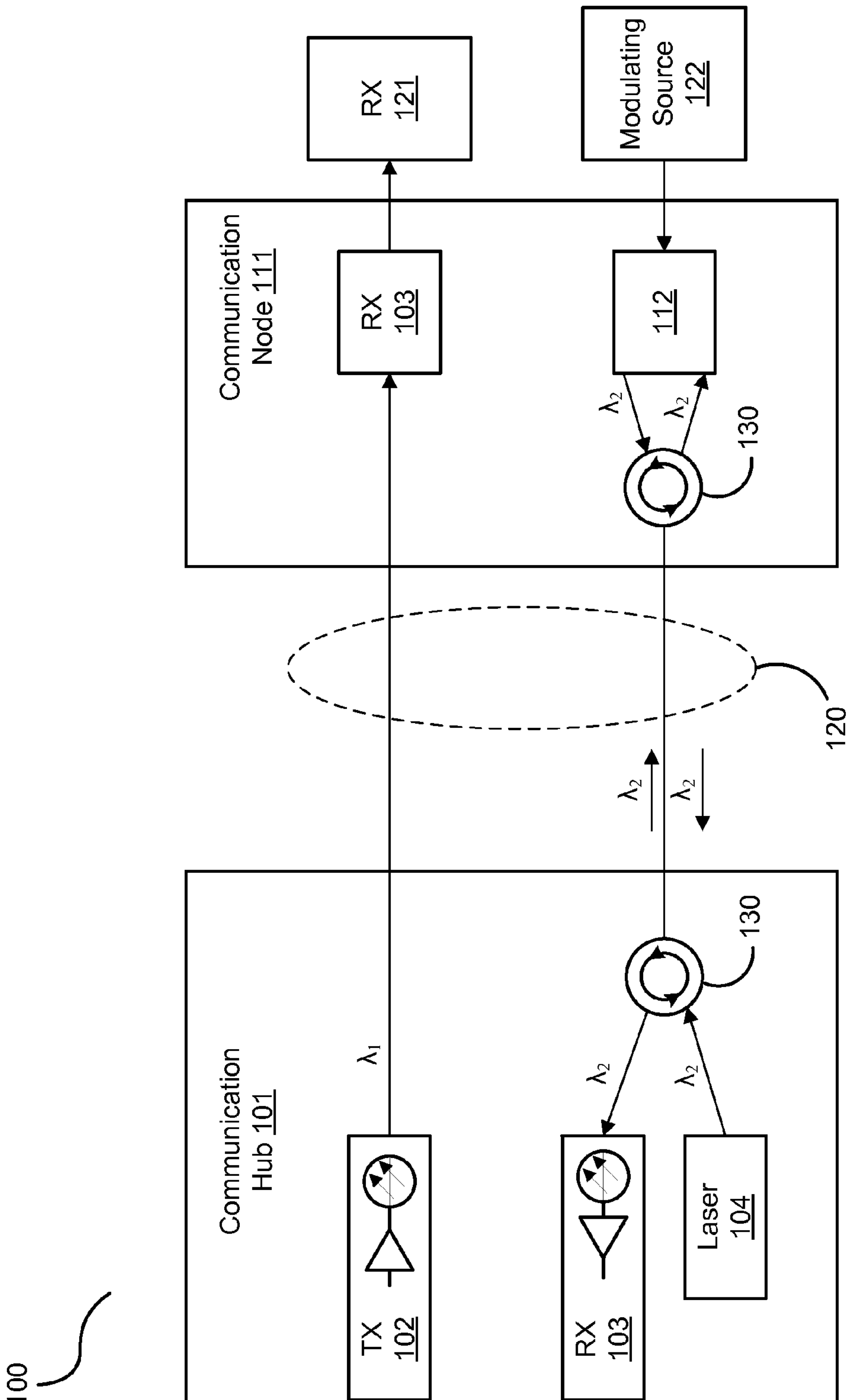

100
Communication Hub 101
TX 102
RX 103
Laser 104
λ_1
λ_2
λ_2
130
λ_2
λ_2
120
Communication Node 111
RX 103
112
λ_2
λ_2
130
RX 121
Modulating Source 122

FIG. 4

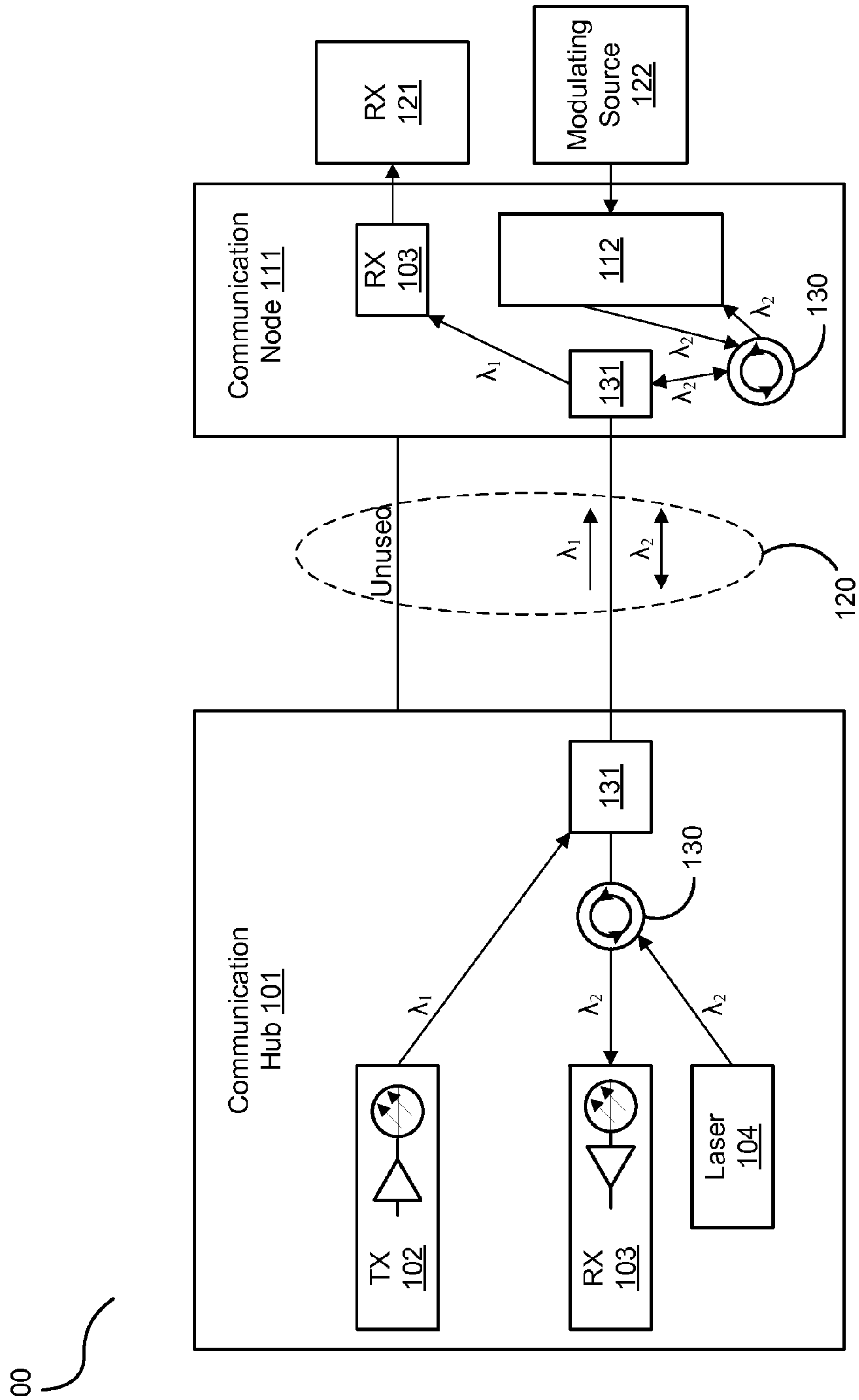
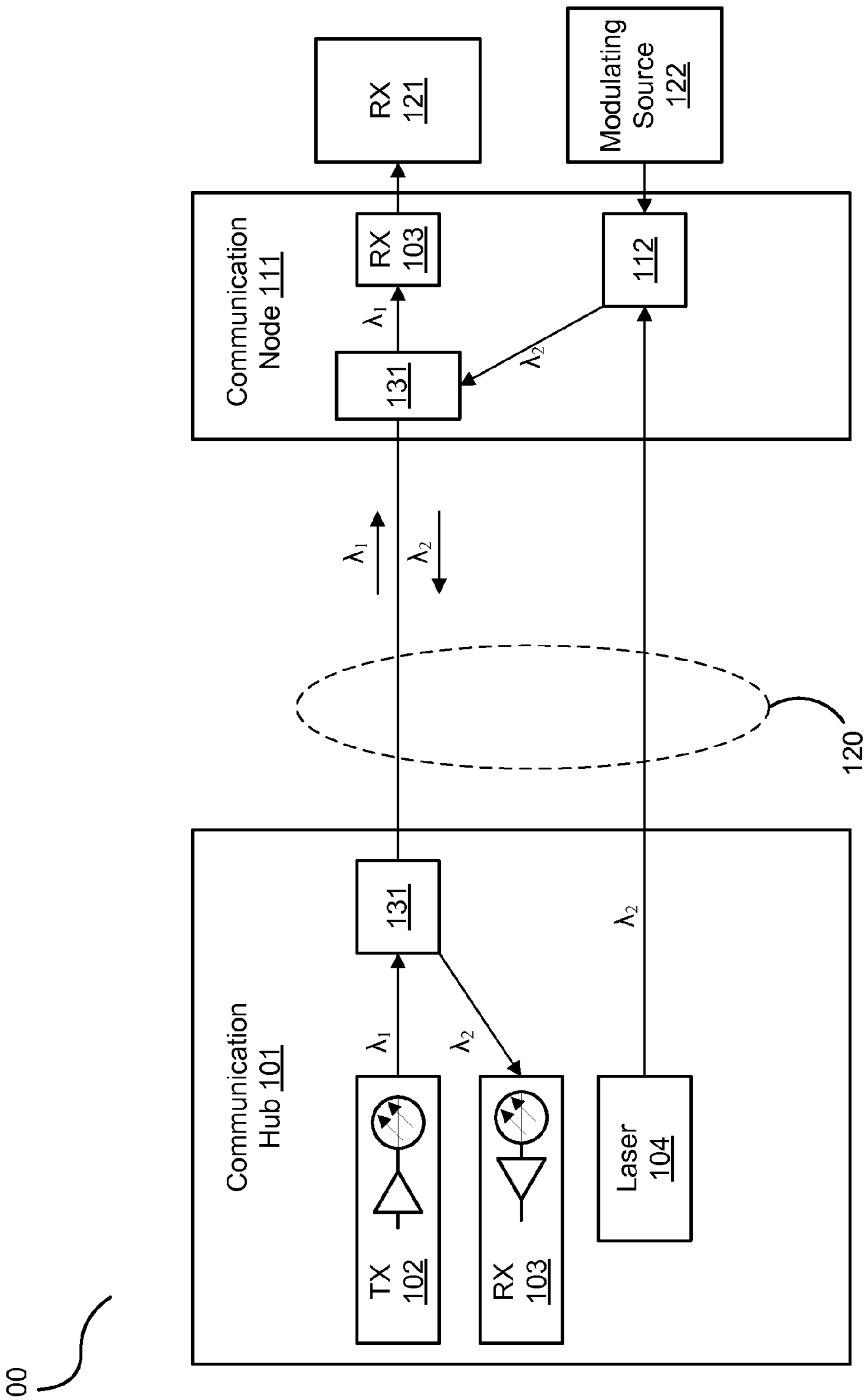

Communication Hub 101
TX 102
RX 103
Laser 104
131
130
Communication Node 111
RX 103
112
131
130
RX 121
Modulating Source 122
Unused
120
100

FIG. 5



100
Communication Hub 101
TX 102
RX 103
Laser 104
131
λ1
λ2
120
Communication Node 111
131
RX 103
112
RX 121
Modulating Source 122

FIG. 6

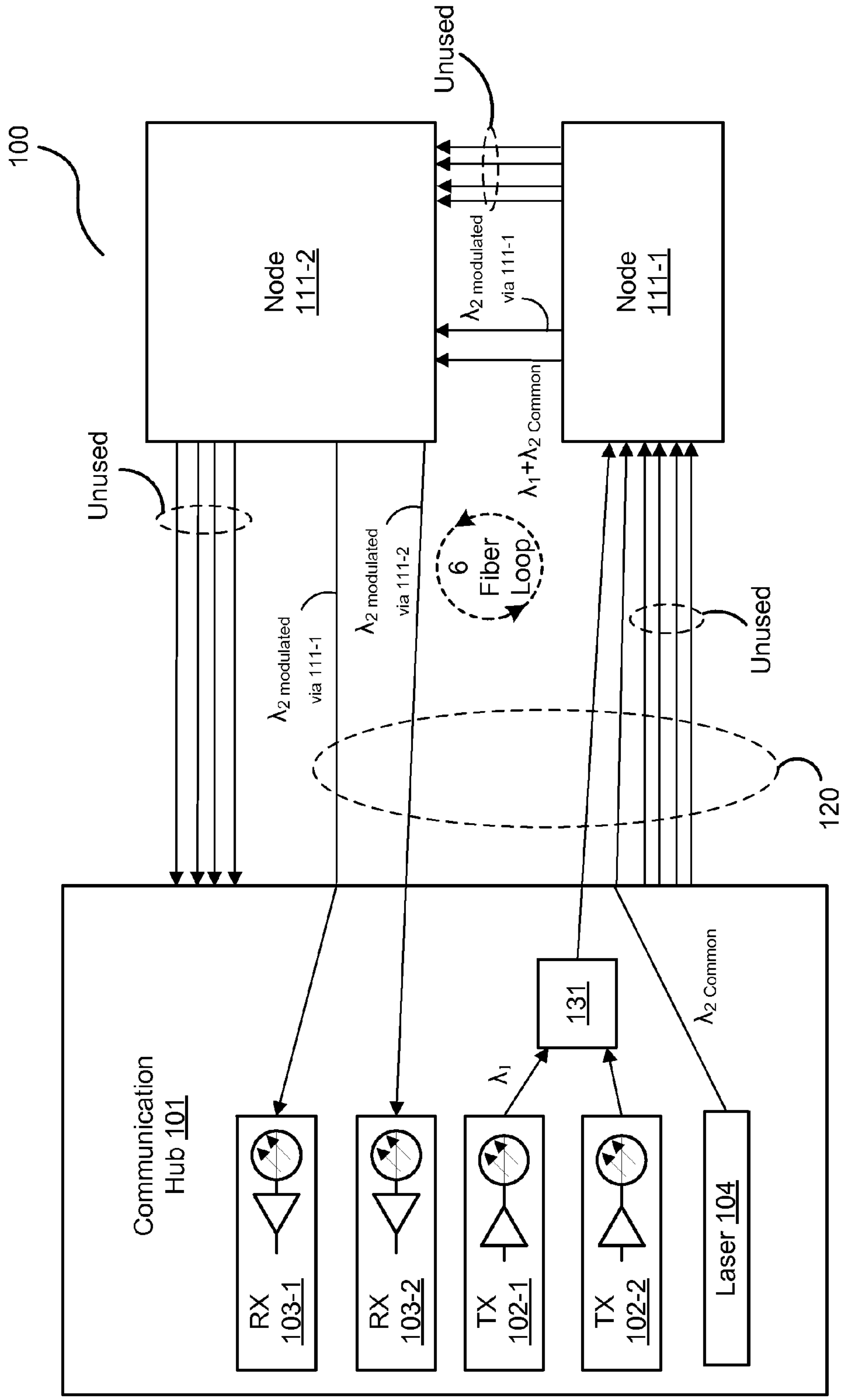

100
Node 111-2
Node 111-1
Unused
Unused
Unused
λ_2 modulated via 111-1
λ_2 modulated via 111-2
λ_2 modulated via 111-1
λ_1+λ_2 Common
6 Fiber Loop
120
Communication Hub 101
RX 103-1
RX 103-2
TX 102-1
TX 102-2
Laser 104
131
λ_1
λ_2 Common

FIG. 7

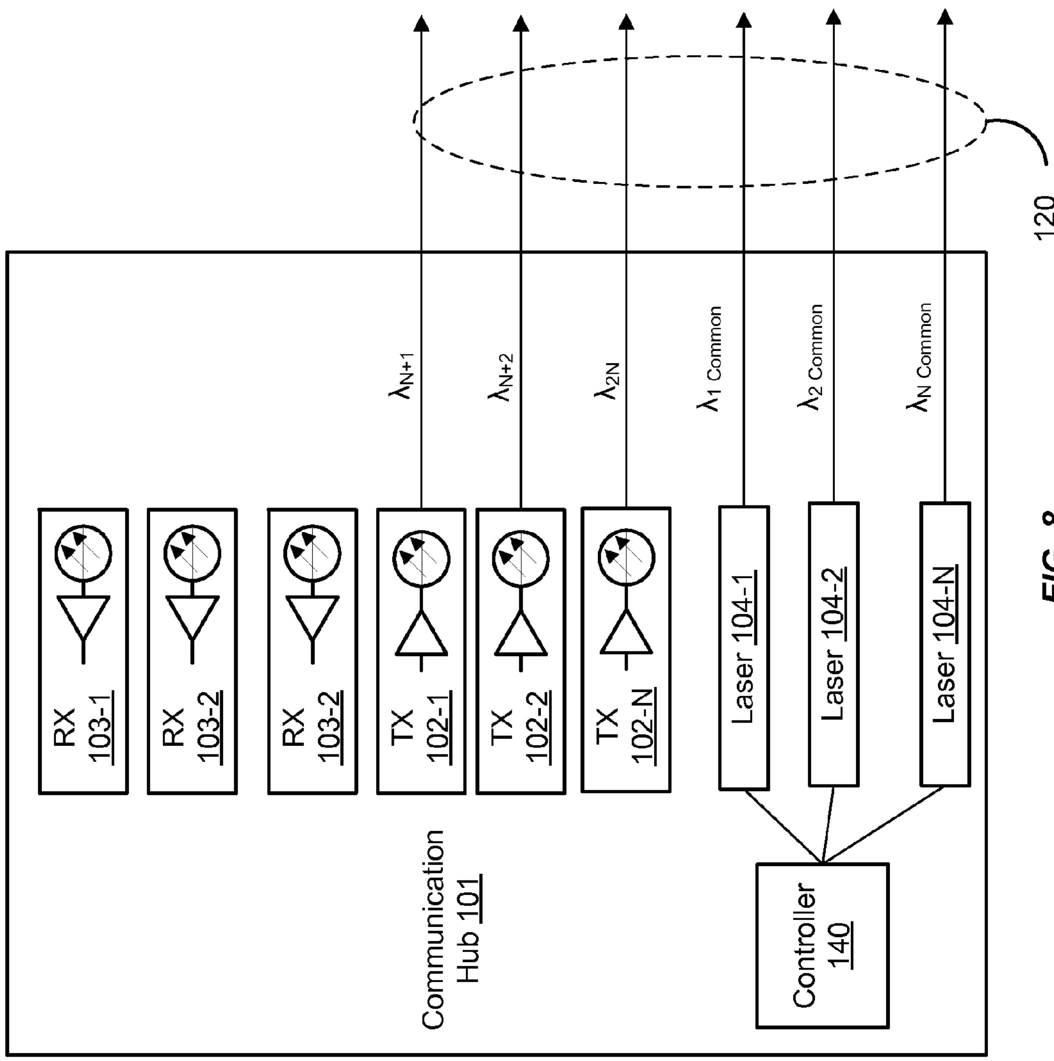
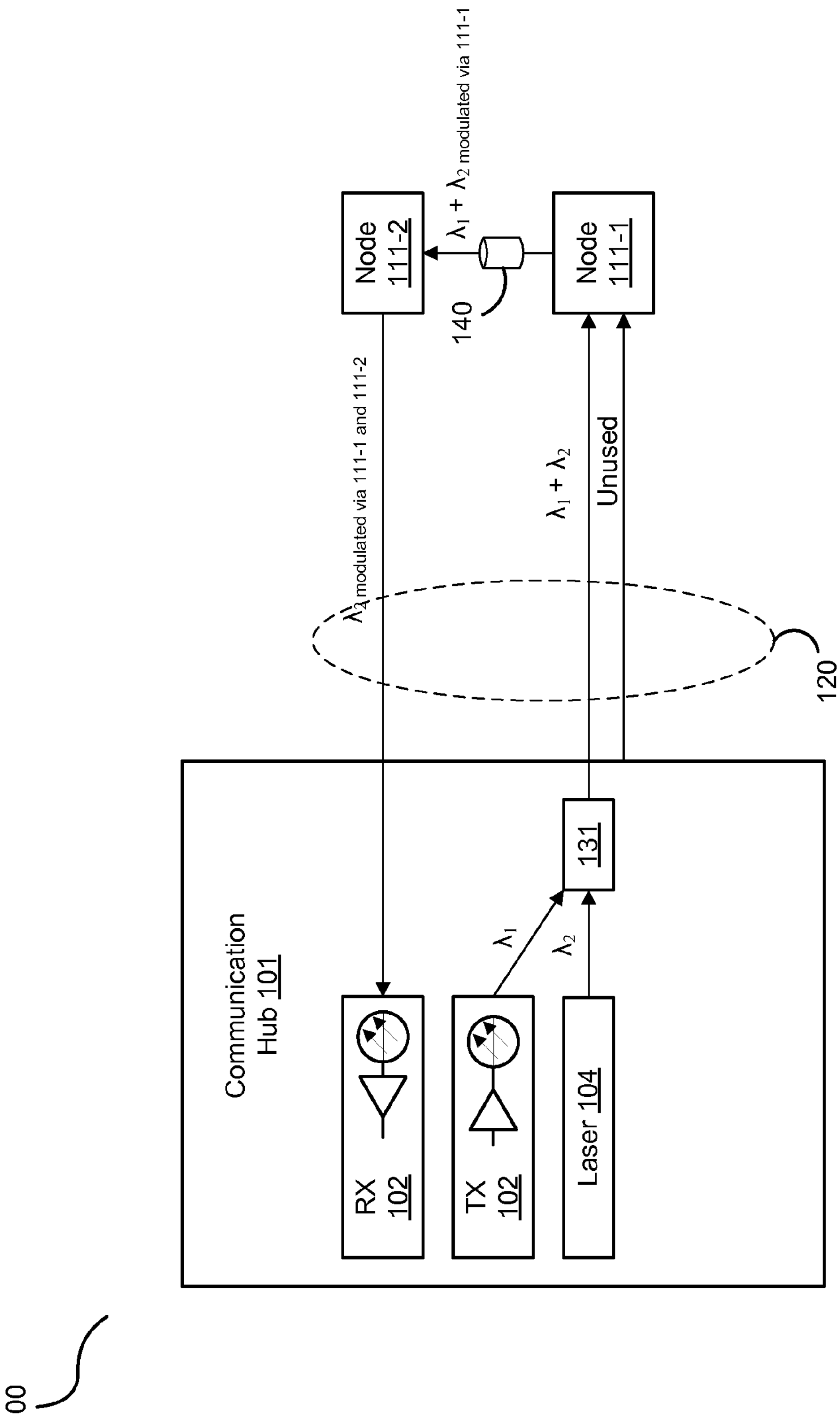

Communication Hub 101
RX 103-1
RX 103-2
RX 103-2
TX 102-1
TX 102-2
TX 102-N
Laser 104-1
Laser 104-2
Laser 104-N
Controller 140
λ_{N+1}
λ_{N+2}
λ_{2N}
$\lambda_{1\ Common}$
$\lambda_{2\ Common}$
$\lambda_{N\ Common}$
120

FIG. 8



100
Communication Hub 101
RX 102
TX 102
Laser 104
131
λ1
λ2
λ1 + λ2
Unused
λ2 modulated via 111-1 and 111-2
120
Node 111-1
Node 111-2
140
λ1 + λ2 modulated via 111-1

FIG. 9

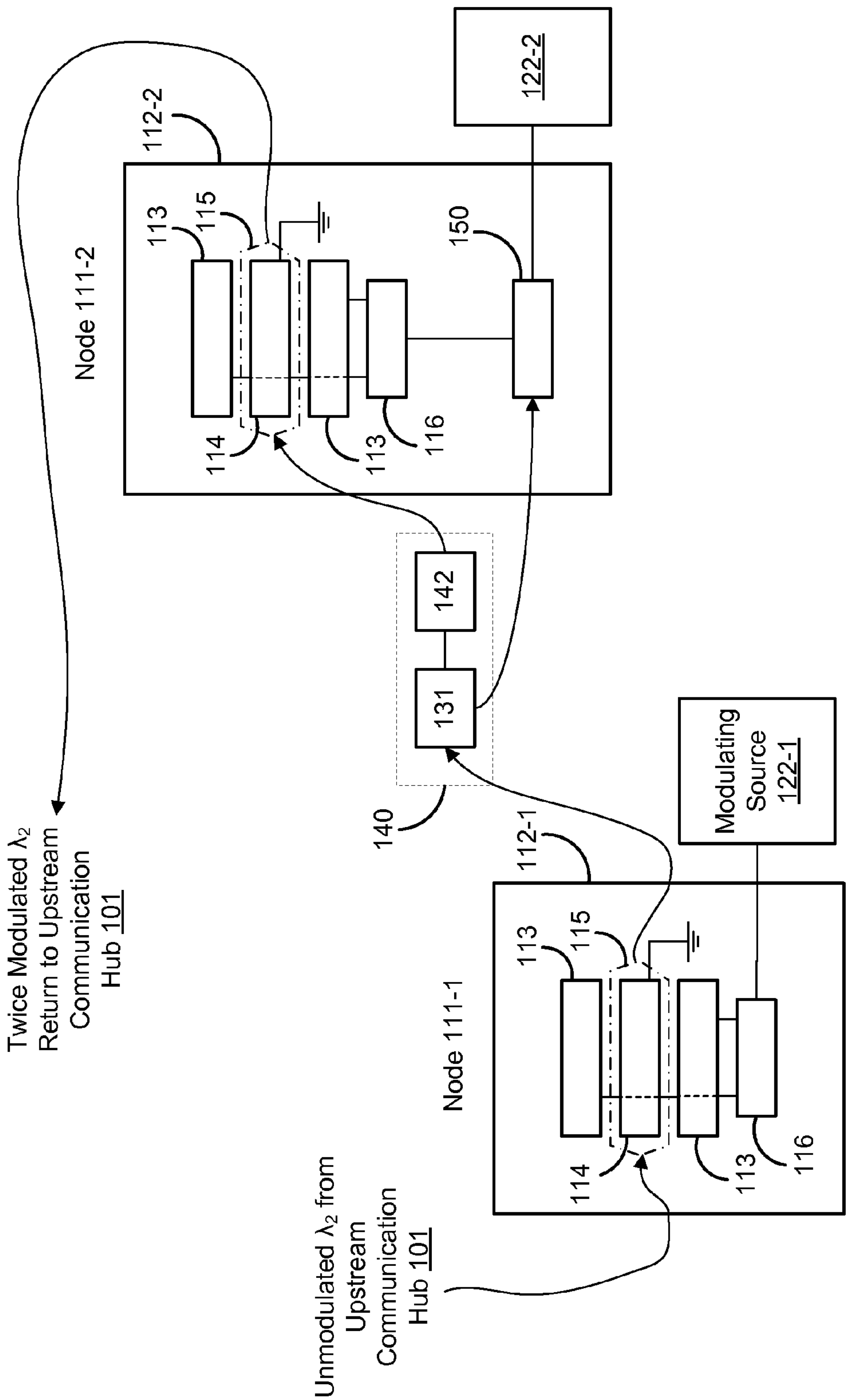
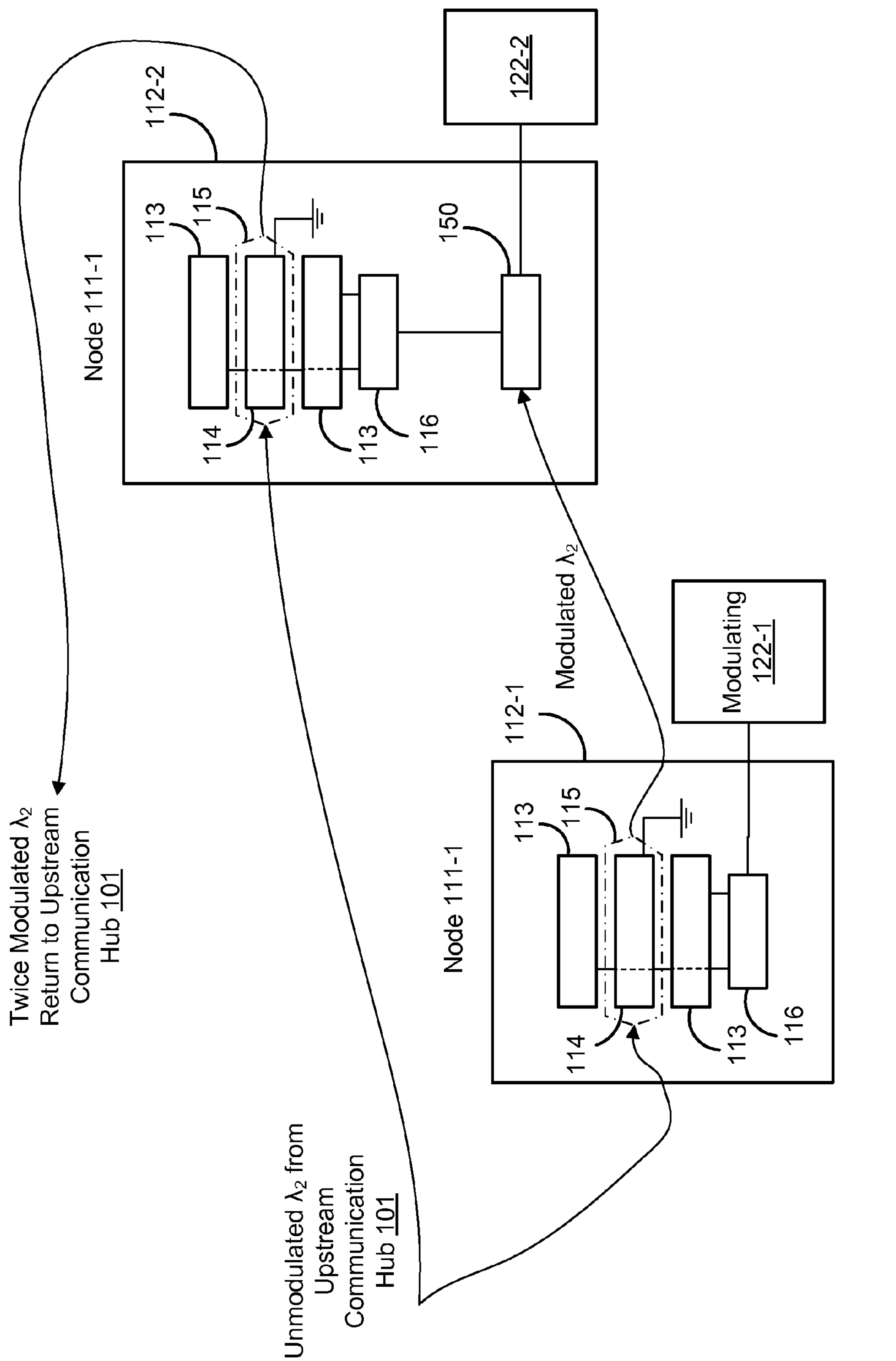

Twice Modulated λ_2 Return to Upstream Communication Hub 101
122-2
112-2
Node 111-2
113
115
150
114
113
116
142
131
140
112-1
Modulating Source 122-1
Node 111-1
113
115
114
113
116
Unmodulated λ_2 from Upstream Communication Hub 101

FIG. 10



Twice Modulated λ_2 Return to Upstream Communication Hub 101
112-2
Node 111-1
113
115
114
113
116
150
122-2
Modulated λ_2
Modulating 122-1
112-1
Node 111-1
113
115
114
113
116
Unmodulated λ_2 from Upstream Communication Hub 101

FIG. 11

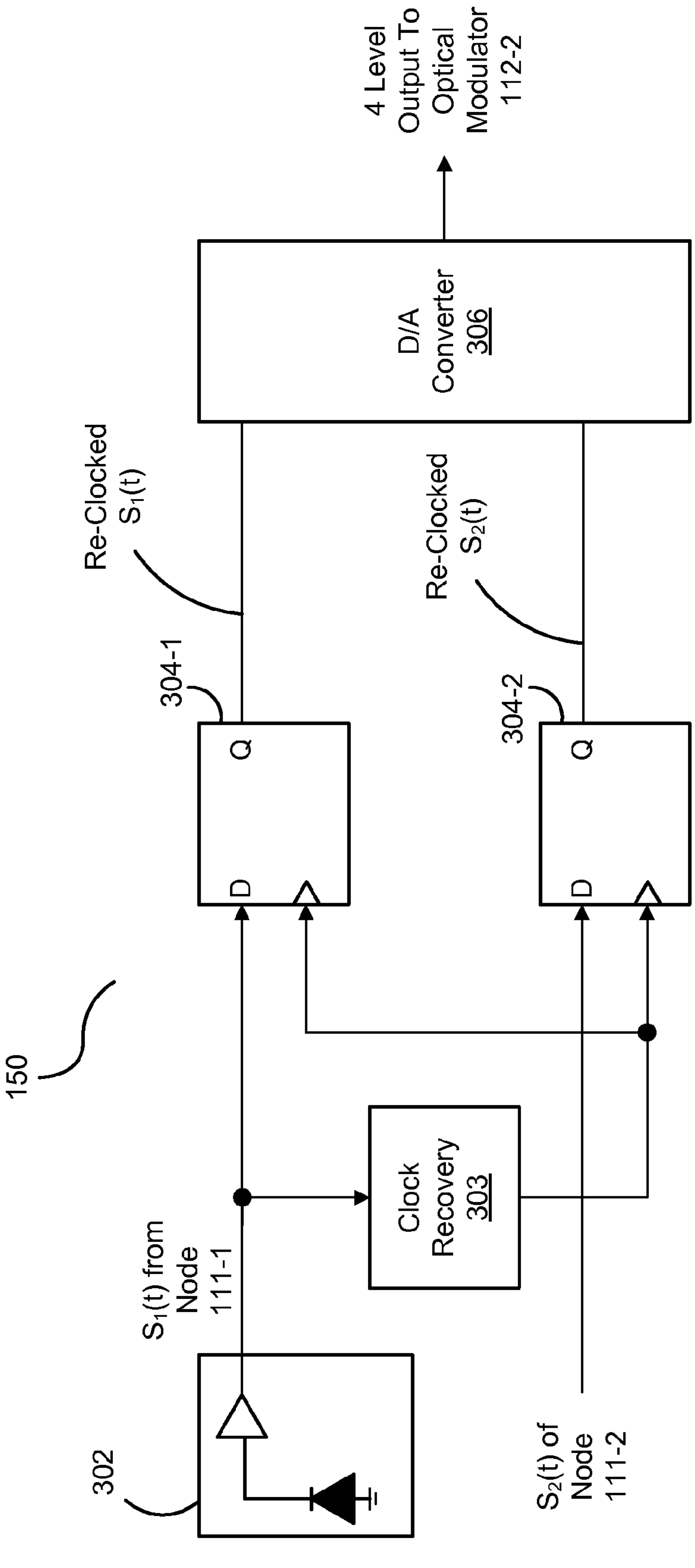

150
302
$S_1(t)$ from Node 111-1
Clock Recovery 303
$S_2(t)$ of Node 111-2
304-1
304-2
D
Q
Re-Clocked $S_1(t)$
Re-Clocked $S_2(t)$
D/A Converter 306
4 Level Output To Optical Modulator 112-2

FIG. 12

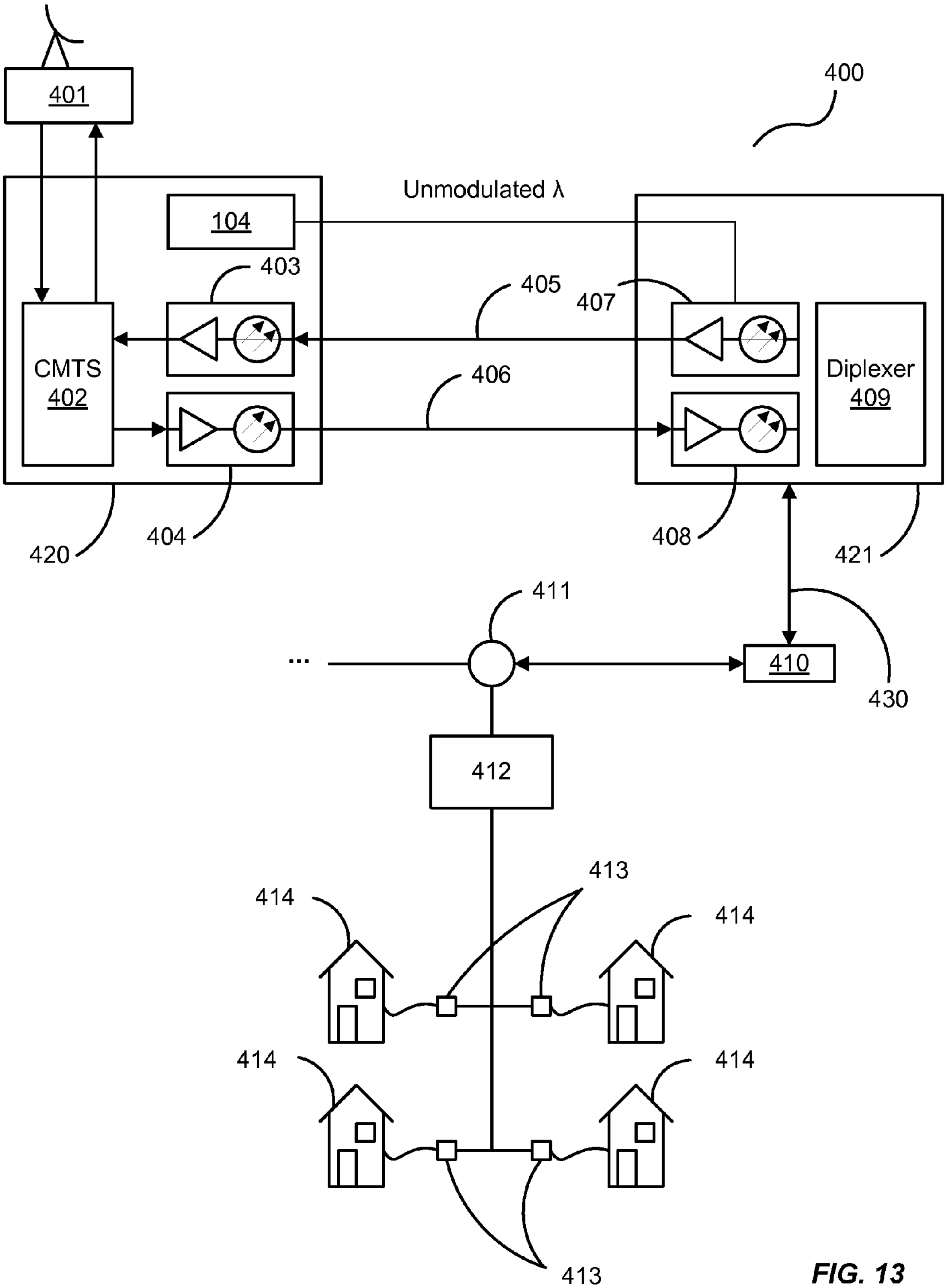

400
401
104
Unmodulated λ
403
405
407
CMTS
402
406
Diplexer
409
420
404
408
421
411
...
410
430
412
413
414
414
414
414
413

FIG. 13

OPTICAL COMMUNICATION SYSTEMS AND METHODS

CROSS REFERENCE TO RELATED APPLICATIONS

This patent application is a non-provisional patent application claiming priority to, and thus the benefit of an earlier filing date from, U.S. Provisional Patent Application No. 61/912,699 (filed Dec. 6, 2013), the entire contents of which are hereby incorporated by reference. This patent application is also related to U.S. patent application Ser. Nos. 14/322,063 and 14/322,093 (filed Jul. 2, 2014), the entire contents of each of which are also incorporated by reference.

BACKGROUND

Higher capacity optical links (e.g., 20 GHz to 30 GHz) place greater demands on directly modulated diode lasers. Wavelength division multiplexing provides some relief for these demands. Newer diode lasers are more stable and exhibit narrower linewidths that make coherent optical communications more practical to implement. But, increasing demands for data continue to present problems in optical communications. And, these newer technologies are not always feasible to implement.

SUMMARY

Systems and methods presented herein provide for optical communications. In one embodiment, a communication system includes a plurality of communication nodes and a communication hub. A bundle of optical fibers optically links the nodes to the communication hub. The communication hub includes a laser operable to propagate unmodulated laser light to a first node along a first of the optical fibers in the bundle. The first node is operable to modulate the laser light with a first modulating signal source, and to propagate the modulated laser light to a second node. The second node is communicatively coupled to a second modulating signal source and to the first node. The second node is operable to optically combine upstream communications from the second modulating signal source with the modulated laser light from the first node, and to propagate the modulated laser light with the upstream communications to the communication hub at a same carrier wavelength.

The various embodiments disclosed herein may be implemented in a variety of ways as a matter of design choice. For example, some embodiments herein are implemented in hardware whereas other embodiments may include processes that are operable to implement and/or operate the hardware. Other exemplary embodiments, including software and firmware, are described below.

BRIEF DESCRIPTION OF THE FIGURES

Some embodiments of the present invention are now described, by way of example only, and with reference to the accompanying drawings. The same reference number represents the same element or the same type of element on all drawings.

FIG. **1** is a block diagram of an exemplary optical communication system.

FIG. **2** is a flowchart illustrating an exemplary process of the optical communication system of FIG. **1**.

FIG. **3** is a block diagram of an exemplary QAM optical modulator.

FIGS. **4-11** are block diagrams of other exemplary optical communication systems.

FIG. **12** is a block diagram of a synchronization module used in a communication node.

FIG. **13** is a block diagram of an exemplary cable television system employing optical systems and methods herein.

DETAILED DESCRIPTION OF THE FIGURES

The figures and the following description illustrate specific exemplary embodiments of the invention. It will thus be appreciated that those skilled in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the invention and are included within the scope of the invention. Furthermore, any examples described herein are intended to aid in understanding the principles of the invention and are to be construed as being without limitation to such specifically recited examples and conditions. As a result, the invention is not limited to the specific embodiments or examples described below.

FIG. **1** is a block diagram of an exemplary optical communication system **100**. The optical communication system **100** includes a communication hub **101** and communications nodes **111-1** and **111-2**. The communication hub **101** and the communication nodes **111** are optically coupled to one another via a plurality of optical communication links **120** (e.g., a bundle of optical fibers). Although illustrated with a two communication nodes **111-1** and **111-2**, the communication hub **101** is a center point of communication activity and may be coupled to even more communication nodes **111** to transmit data to the communication nodes **111**. Thus, the communication hub **101** is any system, device, software, or combination thereof operable to optically communicate data to one or more communication nodes **111**.

The communication hub **101** comprises an optical transmitter **102** that optically transmits data to the communication nodes **111-1** and **111-2** over one or more of the optical links **120** at a wavelength λ_1 of light. The communication nodes **111-1** and **111-2** comprise an optical receiver (not shown) that is optically coupled to the optical transmitter **102** of the communication hub **101** via the optical links **120**. The optical receiver receives optical communications from the optical transmitter **102** of the communication hub **101** and converts the data thereof to electronic data. In this regard, the communication node **111** may transfer the electronic data to one or more receivers or data connections (e.g., over radio frequency, RF, via coaxial cable) to facilitate the transfer of data, video, audio, and the like from the communication hub **101** to a plurality of subscribers (e.g., households and businesses).

Each communication node **111** is also operable to optically communicate data to the communication hub **101** over one or more of the optical links **120**. Each node **111** is configured with an optical modulator (optical modulator **112** shown below) that is operable to modulate laser light with a modulating source. For example, the optical modulator may be a Mach-Zehnder optical modulator communicatively coupled to a coaxial cable conveying an RF signal which is used to phase modulate laser light in a gain medium of the optical modulator, although other modulating signal sources may be used including digital signal sources. Thus, with respect to the preceding, the communication node **111** is any system, device, software, or combination thereof operable to optically communicate with a communication hub **111**.

To improve the optical integrity of the communication system **100**, and more specifically the optical transmissions from the communication node **111**, the communication hub

101 is configured with a laser **104** that propagates laser light to the optical modulators over one or more of the optical links **120** for return optical communications by the nodes **111** (e.g., "upstream" communications). For example, diode lasers over time can degrade in terms of performance when they are exposed to harsh conditions where communication nodes **111** may be placed. Thus, the communication hub **101** may incorporate the laser **104** within an environmentally controlled climate to maintain consistent performance for the laser **104**. The laser **104** propagates unmodulated laser light to the optical modulators of the nodes **111** over the optical communication links **120** such that the communication nodes **111** can modulate the laser light via their respective signal sources and convey the data thereof to an optical receiver **103** of the communication hub **101**.

In some embodiments, the optical modulator may include a polarization controller. For example, the optical modulator may exhibit polarization sensitivity due to longer optical links **120** that can be marginalized or otherwise reduced through the use of a polarization controller that modifies the polarization of the light to the optical modulator in a desirable fashion. The polarization controller may also be used for the purposes of polarization division multiplexing. For example, a first communication signal may be conveyed via light in a particular polarization. To increase the capacity, a second communication signal may be conveyed on the same optical link **120** at a polarization that is orthogonal to the first communication signal, potentially doubling the capacity. Additional details regarding the optical modulator and its various components (e.g., transmission line electrodes, a phase shifter, and a transmitter) are shown and described in FIG. **3**. An exemplary operation of the optical communication system **100** is now shown and described the process **200** of FIG. **2**.

FIG. **2** is a flowchart illustrating one exemplary process **200** of the optical communication system **100**. In this embodiment, the process **200** initiates when an optical link **120** is established between the communication hub **101** and the communication nodes **111-1** and **111-2**, in the process element **201**. Establishment of the optical link **120** generally includes establishing communications between the communication hub **101** and the communication nodes **111-1** and **111-2** over one or more optical fibers run (e.g., buried underground) between the communication hub **101** and the optical modulators of the communication nodes **111-1** and **111-2**.

The laser **104** propagates unmodulated laser light to the node **111-1** along a first of the optical fibers at a wavelength λ_2 of light, in the process element **202**. That node modulates the laser light with a first modulating signal source (e.g., an RF signal conveyed over coaxial cable to the node **111-1**), in the process element **203**. After the light is modulated, the node **111-1** propagates the modulated light to the node **111-2**, in the process element **204**, such that the node **111-2** can convey the upstream communications of the node **111-1** back to the communication hub **101**.

First, however, the node **111-2** combines its upstream communications from another modulating signal source (e.g., another RF signal conveyed over coaxial cable to the node **111-2**), in the process element **205**, with the modulated laser light from the node **111-1**. For example, the unmodulated laser light from the laser **104** may be propagated over one of the fiber optic links **120** to the node **111-1** where it is split and propagated to the node **111-2**. The node **111-1** may then modulate that light and propagate it to the node **111-2**. The node **111-2** may then convert the modulated light from the node **111-1** to an electrical signal and combine that signal with the signal conveyed to the node **111-2**. From there, the node **111-2** may modulate the unmodulated light at the wavelength λ_2 with the combined signal to propagate both upstream communications from the nodes **111-1** and **111-2** to the communication hub **101** or to another node **111** at the same carrier wavelength, in the process element **206**.

The embodiments disclosed herein provide a pathway for higher optical capacities as well as the ability to optimize communications over existing optical links. For example, a traditional cable television node is used to translate amplitude modulated light from a communication hub to an RF signal covering less than 1 GHz of bandwidth. The RF signal is then propagated to households and businesses. The modulation imprinted on an optical carrier can comprise 160 multiplexed digital quadrature amplitude modulation (QAM) or analog National Television System Committee (NTSC) subcarriers. The node has an optical receiver operable to receive signals between about 50 MHz to 1002 MHz. The node also has a laser transmitter intended for upstream return information of about 100 MHz. Increasing demand for data over the limited upstream spectrum has led to the exploration of other upstream ranges of 5 MHz to 85 MHz and 5 MHz to 204 MHz, which generally results in a change to downstream frequency ranges.

NTSC analog signals and other signals can exhibit high linearity and dynamic range. Laser requirements with such parameters are generally very stringent. And, higher signal-to-noise ratios (SNRs) are typically required to support higher order modulations. For example, next generation Data Over Cable Service Interface Specification (DOCSIS) systems, such as DOCSIS 3.1, have been designed to support 4,096 state QAM and 16,384 state QAM. And, the SNR for these modulations generally needs to be significantly higher. It should be noted, however, that NTSC is a United States standard and that the embodiments disclosed herein may also be useful/advantageous with other signaling standards such as those used in the European cable television industry.

Demands on upstream communications from communication nodes (e.g., from cable television data subscribers), such as the communication node **111**, are also pushing cable television operators to use higher quality diode lasers. As upstream communications may encounter many types of interference, SNR is even more important when employing QAM.

One way to increase capacity and alleviate the need for higher SNR and more exotic modulations could be to simply increase the number of optical links between the communication hub of the cable television network (e.g., the communication hub **101**) and the communication node. However, when optical fibers were initially laid to establish the optical links, they were done so in a "loop" configuration in which the communication hub is connected to a plurality of communication nodes cascaded in series with the last communication node in the link connecting back to the communication hub. And, there were only a few fibers dedicated to each node because communication nodes were originally designed to cover **500** to **1000** homes with a fiber bundle connecting these nodes via six to twelve fiber strands. So, increasing the number of optical links to accommodate ever-increasing capacity would mean laying down and burying new bundles of optical fiber, a costly and labor-intensive effort.

Moreover, a node is typically configured in a harsher operating environment than the communication hub. For example, the communication hub typically has sophisticated equipment that needs to be maintained and housed in a stable operating environment. The nodes, however, are typically located in boxes outdoors and have limited space (e.g., due to real estate covenants, property owner rights, etc.). These harsher operating environments eventually degrade performance of diode lasers and generally preclude the use of more sophisticated lasers when higher capacity is being sought after. By moving the laser **104** to the more climate controlled environment of the communication hub **101**, laser performance can be extended and even improved. Of course, this is just one example of how the system **100** may be implemented. Other exemplary embodiments are shown and described below.

FIG. **3** is a block diagram of an exemplary QAM optical modulator **112**. In this embodiment, the QAM optical modulator **112** comprises a plurality of "sub-optical modulators" **112-1**, **112-2**, and **112-3**. Each optical modulator **112**, in this embodiment, is configured in a Mach Zehnder architecture. In this regard, each optical modulator **112** includes two coupled phase shifters **114** (e.g., an electrode, a crystal medium, a gain medium, or any combination thereof), a pair of optical waveguides to carry the optical signal in the phase shifters **114**, a pair of transmission line electrodes **113** to modify the effective length of the optical path through electrical stimulation within the coupled phase shifters **114**, and a transmitter **116** operable to convey the signal from the source **122** to the electrodes **113**.

Each optical modulator **112** splits the unmodulated light into its corresponding pair of waveguides **115** around its corresponding coupled phase shifters **114**. As such, the optical waveguides **115** split the unmodulated light into two phase shifted branches and recombine after modulation by the transmitter **116** to form, after the interaction of the two phase shifted branches, an amplitude and phase modulated signal. Along the portion where the optical waveguide **115** splits in two, the electrodes **113** may be configured as transmission lines to achieve relatively high modulation frequencies (e.g., a 100 GHz frequency response).

With this in mind, the optical modulator **112-1** receives unmodulated laser light from the laser **104** along the optical link **120** and modulates the light with a signal from a source **122** via the coupled phase shifters **114-1**. The optical modulator **112-2** also receives the unmodulated laser light from the laser **104** (i.e., at the same wavelength) and modulates that light with a signal from the same or another source **122** via the coupled phase shifters **114-2**. The two phase shift modulated signals from the optical modulators **112-1** and **112-2** are then propagated to the optical modulator **112-3** to combine as a QAM signal via the coupled phase shifters **114-3** and the transmitter **116-3**. For example, the transmitter **116-3** may provide a $\pi/2$ phase offset that offsets the two signals from the optical modulators **112-1** and **112-2** by 90° from one another to form the Quadrature Phase Shift Keyed (QPSK) signal when the modulators **112-1** and **112-2** generate a 2-level optical signal. By amplitude modulating the input signals to the optical modulators **112-1** and **112-2** beyond 2 levels via the transmitters **116-1** and **116-2**, respectively, the QPSK signal becomes a higher state QAM signal (e.g., 16 state QAM, 64 state QAM) after the 90 degree phase-shift applied by the optical modulator **112-3**.

The optical waveguide pairs **115**, in this embodiment, are illustrated between the electrodes **113**. However, depending on the crystal characteristics of the coupled phase shifters **114**, the transmission line electrodes **113** may be configured above the waveguide pairs **115** within the coupled phase shifters **114**. The coupled phase shifters **114** center electrode **113** is grounded and the top and bottom electrodes **113** typically have equal but opposite sign voltages to achieve equal but opposite sign phase shifts with respect to the same drive voltage.

Generally, Mach Zehnder optical modulator architectures can be manufactured from materials exhibiting certain electro-optic effects that change the index of refraction based on the voltage applied. As the index of refraction changes, the effective dimension of the optical path changes and a phase shift occurs. Lithium niobate, indium phosphide, and various polymers are some of the materials that may be used to implement the coupled phase shifters **114**. In some embodiments, the phase shifter **114** may be configured with a material that provides an optical gain (e.g., an optical gain medium) to the modulated signal.

Mach Zehnder architectures can be fairly sensitive to polarization changes. Accordingly, the communication system **100** and/or any of the optical modulators **112** involved may be configured with a polarization controller **119** as described above to compensate for a shift in polarization rotation.

The transmitter **116** may be configured in a variety of ways depending on the input signal being used to modulate the unmodulated light from the laser **104**. For example, assuming that the signal from the source **122** is an analog signal (e.g., an RF signal), the transmitter **116** may include an analog to digital converter that converts the analog signal to a digital signal which is thereby used to modulate the unmodulated light via the bipolar stimulation of the electrodes **113**. In another implementation, the digital signal generates a multi-level stimulation that is used to generate an optical QAM signal. In yet another implementation, the transmitter takes the RF source and amplifies it to an optimum level to drive the optical modulator **112** using certain functionality, such as automatic gain control.

Additionally, the signal driving the optical modulator **112** can be conditioned so that it is optimized for high frequency operation. For example, a mismatch can exist between the propagation speed of an electrical signal on electrical transmission lines which connect to the electrodes **113** and the propagation speed through the optical waveguides. The optical signals on the optical waveguide modulated by the electrical signal where the phase shift and/or optical gain of the coupled phase shifters **114** take place can experience distortion. Thus, the electrical signals driving the optical modulator **112** can be conditioned to achieve more linearity (e.g., via pre-distortion conditioning techniques).

As mentioned, the signal driving the optical modulator **112** may be a digital signal that actually improves optical performance. For example, RF signal digitization along increased digital capacity lines can be used to increase transmission performance compared to an analog optical link. To accomplish such, the transmitter **116** may be configured with an analog to digital converter that samples the entire RF signal. In any case, the signal driving circuitry may include delay functionality to allow for other features such as time division multiplexing. A clock input to synchronize re-modulation may be used for implementing other multiplexing techniques. An example of such is illustrated in FIG. **12**.

FIGS. **4-11** are block diagrams of other exemplary optical communication systems. Each of these embodiments may be used to optimize optical communications and increase capacity, more particularly in the upstream optical communications. In FIG. **4**, a communication hub **101** is operable to optically transmit data from an optical transmitter **102** to an optical receiver **103** of a communication node **111**. In this embodiment, the optical data transmitted to the communication node **111** is propagated along an optical link **120** at a wavelength λ_1. The optical receiver **103** of the communication node **111** may then convert the received signal to an analog RF signal conveyed over coaxial cable to a receiver **121**.

The communication hub **101** is also configured with an optical receiver **103** that is similarly used to convert a received signal from an external modulator **112** of the communication node **111**. As with the previous embodiments, the laser **104** is configured with the communication hub **101** to transmit unmodulated light along an optical link **120**. In this embodiment, the laser **104** propagates light at a wavelength λ_2 to the external modulator **112** in the communication node **111**. The communication node **111** then modulates the light λ_2 at the external modulator **112** in the communication node **111** using the signal from the modulating source **122** (e.g., an RF signal propagated along a coaxial cable).

To assist in reducing the number of optical links **120** used in transmitting data from the communication node **111** to the communication hub **101**, the communication hub **101** also employs an optical circulator **130**. The optical circulator is used to separate optical signals traveling along an optical link **120** in opposite directions. For example, the optical circulator **130** may be a three-port device such that light entering any port exits from the next so as to achieve bi-directional propagation over a single optical link **120**. Thus, the laser **104** can propagate the modulated light at the wavelength λ_2 to the external modulator **112** of the communication node **111** for modulation via the modulating source **122** and have the modulated light at the wavelength λ_2 propagated along the same optical link **120** to the receiver **103** of the communication hub **101**, thereby reducing the need for an additional optical link **120** as illustrated in the embodiment of FIG. **1**.

The embodiment in FIG. **4** is exemplarily illustrated with the transmitter **102** of the communication hub **101** transmitting light at the light at the wavelength λ_1 and the laser **104** transmitting light at the wavelength λ_2. One reason for this leads to the embodiment illustrated in FIG. **5** which allows for yet another optical link **120** to be removed and preserved for other uses such as higher capacity. For example, in FIG. **5**, the communication hub **101** optically transmits optical data from the transmitter **102** at a wavelength λ_1. The laser **104** in the communication hub **101** propagates unmodulated light at a wavelength λ_2 to the optical circulator **130** into the communication node **111**. The outbound unmodulated light from the laser **104** is then combined with the optical data at the wavelength λ_1 from the external modulator **112** with the optical element **131** (e.g., a diffraction grating or an optical splitter) past the optical circulator **130** to propagate both wavelengths of light along the same optical link **120**.

The combined light of wavelengths λ_1 and λ_2 arrives at the communication node **111** and are separated by another optical element **131** (e.g., a splitter or diffraction grating). The optical data of the wavelength λ_1 from the optical transmitter **102** of the communication hub **101** then propagates to the receiver **103** of the communication node **111**. And, the unmodulated light of the wavelength λ_2 propagates to the optical circulator **130** of the communication node **111** where it is modulated by the external modulator **112** with the signal of the modulating source **122**. The modulated light from the external modulator **112** then propagates to the optical circulator **130** so that it can propagate along the same optical link **120** as the unmodulated light (i.e., in the opposite direction). The modulated light is then split by the optical element **131** such that it may be received by the receiver **103** of the communication hub **101** (e.g., after passing through the optical circulator **130**). As can be seen, the different wavelengths being combined on the same optical link **120** allows for another optical link to be freed for other use (e.g., higher capacity).

In FIG. **6**, the communication system **100** propagates the modulated light from the laser **104** at the wavelength λ_2 directly to the external modulator **112** of the communication node **111** for modulation. Thereafter, the modulated light from the external modulator **112** of the communication node **111** is combined with the incoming light at the wavelength λ_1 from the transmitter **102** of the communication hub **101** at the optical element **131** of the communication node **111** (e.g., again, an optical splitter or a diffraction grating). The modulated light at the wavelength λ_2 is then propagated along the same optical link **120** as the incoming light at the wavelength λ_1 and is split off from the optical link **120** with the optical element **131** in the communication hub **101** where it is received by the receiver **103**.

FIG. **7** illustrates the communication system **100** with a plurality of cascaded nodes **111-1** and **111-2**. In this embodiment, the communication hub **101** has a receiver **103** for each of the communication nodes **111**. The receiver **103-1** receives upstream communications from the node **111-1** and the receiver **103-2** receives upstream communications from the node **111-2**. The communication hub **101** again comprises a transmitter **102-1** that transmits optical communications at a wavelength λ_1 to the node **111-1** and a transmitter **102-2** that transmits optical communications at a wavelength λ_2 to the node **111-2**. The communication hub **101** also comprises a laser **104** operable to propagate light at a common unmodulated wavelength λ_2 to each of the nodes **111-1** and **111-2**.

As can be seen in this embodiment, the communication hub **101** is optically coupled to the node **111-1** with six optical links **120**. This embodiment is intended to illustrate how an optical network can be configured with a bundle of optical fibers. For example, in a cable television network, the communication hub **101** is connected to a plurality of nodes via a plurality of optical links **120**. Generally, this is implemented with a plurality of optical fibers being laid underground or above ground in a "loop" configuration, with the optical fibers usually being configured in bundles of multiple of six optical fibers. And, each node **111** has its own dedicated optical fiber for upstream communications to the communication hub **101**. Thus, if there are 5 nodes **111** in a loop, then all optical fibers in a bundle of six optical fibers are used because one of the optical fibers is common to each node **111** for downstream communications that uses separate wavelengths and can be aggregated into a single optical fiber coming from the communication hub **101**.

Once laid, the bundle of optical fibers is intended to be a somewhat permanent fixture. Thus, when additional homes connect to a particular node **111** and/or when additional capacity is required of a node **111**, communications over the fixed number of optical fibers is at a premium.

This embodiment and others below alleviate some of the problems associated with fixed bundles of optical fibers. In this embodiment, the node **111-1** is optically coupled to the communication hub **101** via six optical links **120**, four of which are shown as being unused because only two nodes **111** are illustrated. The communication hub **101** transmits communications to each of the nodes **111-1** and **111-2** along a common optical link **120** respectively at the wavelengths λ_1 and λ_2. The communication hub **101** propagates unmodulated light at the wavelength λ_2 along another common optical link **120**. The node **111-1** modulates the light at the wavelength λ_2 via its modulating source **122** (not shown) and propagates the modulated light to the node **111-2** along yet another of the optical links **120**. The node **111-1** also propagates the unmodulated light at the wavelength λ_2 to the node **111-2** along an unused fiber so that it can modulate it via its modulating source **122** (not shown) and propagate its upstream communications to the communication hub **101**.

The node **111-2**, being the last node in the loop before the communication hub **101**, can simply modulate the light at the wavelength λ_2 and propagate it along the same optical link used to carry the unmodulated light at the wavelength λ_2 to the node **111-2**. Thus, four optical links **120** remain unused from the node **111-2** to the communication hub **101**, meaning there are 4 additional optical links **120** that could be used for additional capacity.

It should be understood that, while the communication system **100** and this embodiment is illustrated with two nodes **111-1** and **111-2**, the invention is not intended be limited to the illustrated embodiment. The communication system **100** can be and typically is configured with more nodes **111** than illustrated in this embodiment.

FIG. **8** illustrates an embodiment in which the communication hub **101** comprises a plurality of lasers **104-1-104**-N (where the reference "N" is merely intended to represent an integer greater than one and not necessarily equal to any other "N" reference used herein), each operating at a particular wavelength λ (i.e., λ_{N+1}-λ_{2N}). The lasers **104-1-104**-N are, like in previous embodiments, operable to propagate unmodulated light to a communication node **111** such that the communication node **111** can modulate the light and propagate it back to the communication hub **101**. The communication hub **101** may selectively couple one or more of the lasers **104-1-104**-N to the communication node **111** over the plurality of optical links **120**.

The communication hub **101**, in this embodiment, includes a temperature/climate controlled environment that allows the lasers **104-1-104**-N to operate with stable output characteristics. This implementation combines configuration flexibility with certain performance improvements. For example, the lasers **104-1-104**-N, being external cavity lasers, may be selected based on the size of the external cavity. In other words, the wavelength necessary to maintain coherent communications with the desired separation in frequency or wavelength may depend on the cavity length. Accordingly, the controller **140** may select a particular laser wavelength for any given node. And, since they are separate wavelengths, the light from lasers **104-1-104**-N can be propagated along a common optical link **120**.

Turning now to FIG. **9**, the communication system **100** in this embodiment provides wavelength multiplexing over the optical links **120** to a plurality of cascaded nodes **111** (e.g., nodes **111-1** and **111-2**). In this embodiment, the communication hub **101** transmits downstream data at a wavelength λ_1 and the laser **104** propagates unmodulated light at a wavelength λ_2. The two wavelengths of light are combined (i.e., multiplexed) at the optical element **131** and propagated to the node **111-1** over a single optical link **120**.

The other optical link **120** between the communication hub **101** and the node **111-1** is again illustrated in this embodiment as being unused for the purposes of showing how installed fiber optic links can be optimized for capacity. As mentioned, the number of optical links **120** may be at a premium. This is particularly true with the trend of "shrinking" node sizes due to capacity increases. For example, in a cable television network, a node **111** may communicatively couple to a plurality of households and businesses via RF over a coaxial cable. As communication capacity demands increase for each of the household and businesses, the node **111** may have less ability to serve those capacity demands. Accordingly, the node **111** shrinks to serve fewer households and businesses and another node **111** is established for those households and businesses removed or otherwise "squeezed out" of the previous node **111**.

Wavelength division multiplexing has been used and will likely continue to be used to alleviate problems associated with fewer optical links due to shrinking node sizes. But, when data rates increase (e.g., 40 Gigabits per second, or Gbps), wavelengths come at a premium. For example, multiple wavelengths λ of light can be propagated along the single optical link **120**. When each wavelength λ of light is used to transmit more capacity, the spectrum used by the transmitter of the wavelengths λ of light are widened. Eventually, the optical link simply runs out of spectrum to transmit, thus requiring more of the fixed number of optical links **120**. In other words, more capacity eventually translates into a higher number of optical links needed which may be impractical when the optical links are already established and buried underground.

There are different ways of multiplexing signals of different nodes **111**. For example, multiplexing can be performed solely in the digital optical domain through coordinated optical re-modulation in a subsequent node **111**. Alternatively, multiplexing may be performed in the electrical domain by detecting, multiplexing data streams, and then modulating the aggregate data stream.

In the digital optical domain, basic modulation of light takes place by changing characteristics of the light (e.g., such as frequency, phase, intensity, etc.). For example, by changing the intensity of a laser between two states, one can provide an amplitude modulated digital signal. By employing more exotic and complex modulation schemes such as QAM, each symbol in the modulation scheme represents multiple bits and therefore can be used to increase capacity in terms of the overall data rate, but at the expense of greater complexity.

In this embodiment, the unmodulated light at the wavelength λ_2 from the laser **104** is split off by the node **111-1** from the communications of the transmitter **102** in the communication hub **101** (i.e., the wavelength λ_2 of light). The node **111-1** then modulates the light at the wavelength λ_2 via its respective modulating source **122** (not shown) and propagates both the downstream communications and the modulated light at the wavelength λ_2 along the same optical link to the node **111-2**. The node **111-2** then splits off the downstream communications from the communication hub **101** and "re-modulates" the light at the wavelength λ_2 modulated by the node **111-1** using its respective modulating source **122** (not shown). The node **111-2** then propagates the light at the wavelength λ_2 modulated by both nodes **111-1** and **111-2** and conveys their respective upstream communications to the receiver **102** of the communication hub **101** over the same optical link **120** and carrier wavelength λ_2.

Such may be implemented using QAM modulation. An optical delay **140** prior to the modulator **112** of the node **111-2** may be used to provide the node **111-1** with sufficient timing for synchronization purposes. Through the use of coherent optical links **120**, this multiplexing scheme can be expanded to more nodes. Thus, the modulation technique may increase with the number of nodes. For example, four nodes **111-1-111-4** each applying a bi-level (2-level) modulation through proper modulation mechanisms may result in a combined 16 state QAM signal being propagated from the node **111-4** to the communication hub **101**. Further modulation techniques are shown and described in FIGS. **10** and **11**.

FIG. **10** is a block diagram of the modulators **112-1** and **112-2** of the nodes **111-1** and **111-2**, respectively. The downstream communications from the communication hub **101** are not shown in this embodiment for the sake of simplicity. Rather, this embodiment only illustrates the modulators **112** so as to show one exemplary implementation of the unmodulated wavelength of light λ_2 that gets modulated by the two nodes **111-1** and **111-2**. Again, it should be noted that the invention is not intended to be limited to any particular number of nodes or their particular configurations as the embodiments herein may be combined in various ways as a matter of design choice.

In this embodiment, the modulator **112-1** of the node **111-1**, being the first node in the cascaded optical loop, receives unmodulated light at the wavelength λ_2 at the gain medium **114** of the modulator **112-1**. The modulator **112-1** modulates that light with its respective modulating source **122-1** (e.g., an RF signal conveyed over coaxial cable) via its transmitter **116**. That modulated light at the wavelength λ_2 is then propagated to the optical delay **140** to synchronize the light for modulation by the modulator **112-2** of the node **111-2**. The optical delay **140** may be configured with the optical element **131** (e.g., a splitter or a diffraction grating) and an optical delay element **142** (e.g., an optical cavity of mirrors such as that found in a Herriott delay line). The optical element **131** splits off a portion of the modulated light at the wavelength λ_2 which is propagated to a synchronization module **150**. The remaining portion of the modulated light at the wavelength λ_2 is propagated to the gain medium **114** of the modulator **112-2**.

The synchronization module **150**, detects the split-off optical signal ahead of time from the same optical signal arriving directly at the modulator. The synchronization module **150** uses that detected signal from the modulator **112-1** to synchronize and condition the modulation signal from modulating source **122-2**. The newly synchronized conditioned electrical modulation signal is then transferred to the transmitter **116** of the modulator **112-2** such that the upstream communications of the node **111-2** can be modulated onto that light at the precise time and at the right amplitude, thereby remodulating light from the modulator **112-1**. From there, the twice modulated light is propagated at the carrier wavelength λ_2 to convey the upstream communications from the both of nodes **111-1** and **111-2** to the communication hub **101**.

FIG. **11** is a block diagram of the modulators **112-1** and **112-2** of the nodes **111-1** and **111-2**, respectively, in another exemplary implementation of cascaded nodes for upstream optical communications. In this embodiment, the unmodulated light at the wavelength λ_2 is split (e.g., via an optical element **131**) before reaching the modulators **112-1** and **112-2**. Thus, each modulator **112** directly receives the unmodulated light which is propagated to their respective gain mediums **114**. The node **111-1** modulates the light at the wavelength λ_2 via its modulating source **122-1** and propagates it to the synchronization module **150** of the node **111-2**. The synchronization module **150** then detect the light, synchronizes the generated electrical signal from the node **111-1** with its modulating source **122-2** and transfers the synchronized/modulated electrical signal to the transmitter **116** of the modulator **111-2** for modulation of the unmodulated light directed to the coupled phase shifters **114** of the modulator **112-2**. The optical signal with the combined modulation of carrier wavelength λ_2 is then propagated to the communication hub **101** to convey the upstream communications of both nodes **111-1** and **111-2**.

The synchronization module **150**, at least in this embodiment, does not add latency due to processing or decoding of the signal. Rather, the synchronization module **150** detects the modulated light from the modulator **112-1** to recover clock and use the clock as the basis for synchronization to aggregate the data streams from the nodes **111-1** and **111-2** so that symbol transitions of the two streams are aligned. One exemplary embodiment of the synchronization module **150** is illustrated in FIG. **12**.

In FIG. **12**, the synchronization module **150** comprises an optical to electrical converter **302** that converts the modulated light at the wavelength λ_2 from the node **111-1** to an analog signal $s_1(t)$. The clock of the analog signal $s_1(t)$ is then recovered by the clock recovery module **303** and transferred to the D flip-flop **304-2** such that the analog signal $s_2(t)$ can be gated with the analog signal $s_1(t)$ via the D flip-flop **304-1**. The re-clocked analog signals $s_1(t)$ and $s_2(t)$ are then converted to digital signals by the D/A (digital to analog) converter **306** as a four level output to the optical modulator **112-2**. This four level digital output is then transferred to the transmitter **116** of the modulator **112-2** so as to QAM modulator the unmodulated light at the wavelength λ_2 propagated to the coupled phase shifters **114** of the modulator **112-2**.

FIG. **13** is a block diagram of an exemplary communication system **500** employing the optical communication concepts described herein. For example, the optical communication concepts disclosed herein may be implemented in a cable television communication system that employs RF signaling techniques across a substantial amount of RF spectrum. An upstream link of the cable television communication system, in this embodiment, provides high speed data services being delivered over devices conforming to the Data Over Cable Service Interface Specification (DOCSIS) specification. The communication system **400** includes a headend **401** configured with a communication hub **420**. The hub **420** is coupled to a node **421** via optical communication links **405** and **406**.

The hub **420** includes a Cable Modem Termination System (CMTS) **402**, an electrical to optical converter **403**, and an optical to electrical converter **404**. The node **421** is similarly configured with an optical to electrical converter **408** and an electrical to optical converter **407**. The analog to digital (A/D) conversion is generally performed by the electrical to optical converters **403** and **407**.

The headend **401** is generally the source for various television signals. Antennas may receive television signals that are converted as necessary and transmitted over fiber optic cables **406** to the node **421** by the hub **420**. Several hubs may be connected to a single headend **401** and the hub **420** may be connected to several nodes **421** by fiber optic cable links **405** and **406**. The CMTS **402** may be configured in the headend **401** or in the hub **420**. The fiber optic links **405** and **406** may be driven by diode lasers, Fabry Perot lasers, distributed feedback (DFB) lasers, as a few examples.

Downstream, in homes/businesses are devices called the Cable Modems (CM; not shown). A CM acts as a host for an Internet Protocol (IP) device such as personal computer. Transmissions from the CMTS **402** to the CM are carried over the downstream portion of the cable television communication system generally from 54 to 860 MHz. Downstream digital transmissions are continuous and are typically monitored by many CMs. Upstream transmissions from the CMs to the CMTS **402** are typically carried in the 5-42 MHz frequency band, the upstream bandwidth being shared by the CMs that are on-line. However, with greater demands for data, additional frequency bands and bandwidths are continuously being considered and tested, including those frequency bands used in the downstream paths.

The CMTS **402** connects the local CM network to the Internet backbone. The CMTS **402** connects to the downstream path through the electrical to optical converter **404** that is connected to the fiber optic cable **406**, which in turn, is connected to the optical to electrical converter **408** at the node **421**. The signal is transmitted to a diplexer **409** that combines the upstream and downstream signals onto a single cable. The diplexer **409** allows the different frequency bands to be combined onto the same cable. The downstream channel width in the United States is generally 6 megahertz with the downstream signals being transmitted in the 54 to 860 MHz band. Upstream signals are presently transmitted between 5 and 42 MHz, but again other larger bands are being considered to provide increased capacity. The various optical modulation concepts herein may be particularly advantageous. However, the invention is not intended to be limited to any particular form of communication system.

After the downstream signal leaves the node **421**, the signal is typically carried by a coaxial cable **430**. At various stages, a power inserter **410** may be used to power the coaxial line equipment, such as amplifiers or other equipment. The signal may be split with a splitter **411** to branch the signal. Further, at various locations, bi-directional amplifiers **412** may boost and even split the signal. Taps **413** along branches provide connections to subscriber's homes **414** and businesses.

Upstream transmissions from subscribers to the hub **420**/headend **401** occur by passing through the same coaxial cable **430** as the downstream signals, in the opposite direction on a different frequency band. The upstream signals are sent typically utilizing Quadrature Amplitude Modulation (QAM) with forward error correction. The upstream signals can employ any level of QAM, such as 8 QAM, 32 QAM, 64 QAM, 128 QAM, 256 QAM, 4,096 QAM and 16,384 QAM. Of course, other modulation techniques such as Synchronous Code Division Multiple Access (S-CDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) can be used, as desired.

Transmissions, in this embodiment, are typically sent in accordance with the DOCSIS standards. The diplexer **409** splits the lower frequency signals from the higher frequency signals so that the lower frequency, upstream signals can be applied to the electrical to optical converter **407** in the upstream path. The electrical to optical converter **407** converts the upstream electrical signals to light waves which are sent through fiber optic cable **405** and received by optical to electrical converter **403** in the node **420**.

Although generally described with respect to the communication hub **101** being "upstream" and the communication node **111** being "downstream", these terms are merely intended to be exemplary. Nor is the invention intended to be limited to cable television systems for any number of wavelengths, nodes **111**, optical links **120**, etc. Rather, the inventive concepts shown and described herein are merely intended to illustrate how optical communications between two components in a communication system can be optimized or otherwise improved. In this regard, the inventive concepts shown and described herein provide certain advantages over traditional optical communications. One advantage includes the signal generation and optical modulation functions being decoupled from one another. External modulators can then handle higher optical power levels leading to a high dynamic range and reduced non-linear distortion.

For example, direct modulation of diode lasers at higher frequencies is generally achieved at the expense of optical power, making data transmissions beyond 20 GHz exceptionally difficult. External modulation means that less optical power can be used and higher data transmissions can be more easily attained. And, decoupling the optical transmitter from the modulator allows one to focus optical efforts on other performance parameters including higher power, higher frequency response, narrower linewidth for better optical coherence, etc. Moreover, the external modulator can be configured to work as both an intensity modulator and as a coherent QAM modulator depending how it is driven, as shown and described above.

Another advantage of these embodiments regards the use of more sophisticated lasers. For example, analog fiber optic links can convey analog RF signals by amplitude modulating light from a diode laser. Used in cable television networks, these signals generally have optimal SNRs that approach 50 dB. However, as capacity requirements in cable television increase, the SNR of analog fiber optic has become the bottleneck in achieving higher efficiency systems because the diode lasers cannot effectively convey the larger bandwidth RF signals of the higher capacities. Thus, cable television networks seek to digitize RF signals, which uses even more bandwidth but at a lower cost because digital processing capabilities have increased substantially.

To do so, higher order QAM modulations can be used to represent many bits per symbol and digitize the entire RF spectrum available to the cable television network. This generally means that more exotic/higher power lasers are used. One such laser the DFB laser. A DFB laser is a type of diode laser, quantum cascade laser, or optical fiber laser where an active region of the device is periodically structured as a diffraction grating. The structure builds a one-dimensional interference grating (Bragg scattering) and the grating provides optical feedback for the laser. These lasers provide much faster data rates (e.g., 10 Gigabits) but they are also temperature dependent. Altering the temperature of the DFB laser causes a pitch of the grating to change due to the refractive index dependence on temperature. So, the DFB laser should be placed in a climate controlled environment such as the communication hub **101** to allow the optical communication system **100** to achieve higher optical power and/or higher capacity.

Another such laser is an external cavity laser. The external cavity laser has a narrower linewidth than DFB lasers and is suitable for coherent communications which result in higher efficiency use of bandwidth due to multiple bits per symbol.

In some embodiments, optical amplifiers such as an erbium doped fiber amplifiers may be used to provide optical amplification over an amplification medium that takes place outside the modulator to compensate for losses in the network due to fiber attenuation. Alternatively or additionally, optical amplifiers may be employed anyplace where light is split to provide additional amplification. And, although the term laser is used herein, other optical sources may be used. Generally, any optical source with narrower linewidths could be used in lieu of the laser **104**.

What is claimed is:

1. A communication system, comprising: a plurality of communication nodes; a communication hub; and a bundle of optical fibers optically linking the nodes to the communication hub, wherein the communication hub includes a laser operable to propagate unmodulated laser light at a first wavelength to a first of the nodes along a first of the optical fibers in the bundle, wherein the first node is operable to first modulate the laser light with upstream communications of the first node from a first modulating signal source coupled to the first node, and to propagate the modulated laser light to a second of the nodes, wherein the second node is communicatively coupled to a second modulating signal source and to the first node, wherein the second node is operable to second modulate upstream communications from the second modulating signal source onto the modulated laser light from the first node, and to propagate the modulated laser light with the upstream communications of the first and second nodes to the communication hub at the first wavelength, and wherein the second node comprises a synchronization module operable to recover clock in the modulated light from the first node, and to combine the upstream communications of the second node with the modulated laser light from the first node by gating the upstream communications of the second node onto the modulated laser light from the first node using the recovered clock.

2. The communication system of claim **1**, wherein:
the communication hub further comprises an optical transmitter that is operable to propagate downstream communications to the first and second nodes.

3. The communication system of claim **2**, wherein:
the optical transmitter is further operable to propagate the downstream communications along a same optical fiber of the bundle as the upstream communications at a different carrier wavelength.

4. The communication system of claim **1**, wherein:
the second node is further operable to combine the upstream communications from the second modulating signal source with the modulated laser light from the first node as a Quadrature Amplitude Modulated signal.

5. The communication system of claim **1**, wherein:
the nodes are connected in series in a loop configuration.

6. The communication system of claim **1**, wherein:
the communication hub is a cable television headend; and
at least one of the communication nodes is operable to provide cable television signals from the headend to a plurality of taps.

7. A method, comprising: optically linking a plurality of nodes to a communication hub;
propagating unmodulated laser light at a first wavelength to a first of the nodes along a first of the optical fibers in the bundle;
first modulating the laser light with upstream communications of the first node from a first modulating signal source coupled to the first node;
propagating the modulated laser light at the first wavelength to a second of the nodes;
second modulating the laser light at the first wavelength, at the second node, with upstream communications of the second node from a second modulating signal source coupled to the second node; propagating the modulated laser light with the upstream communications of the first and second nodes to the communication hub at the first wavelength; recovering clock, at the second node, in the modulated light from the first node; and combining the upstream communications of the second node with the modulated laser light from the first node by gating the upstream communications of the second node onto the modulated laser light from the first node using the recovered clock.

8. The method of claim **7**, further comprising:
propagating downstream communications to the first and second nodes.

9. The method of claim **8**, further comprising:
propagating the downstream communications along a same optical fiber of the bundle as the upstream communications at a different carrier wavelength.

10. The method of claim **7**, further comprising:
combining the upstream communications from the second modulating signal source with the modulated laser light from the first node as a Quadrature Amplitude Modulated signal.

11. The method of claim **7**, wherein:
the nodes are connected in series in a loop configuration.

12. The method of claim **7**, wherein:
the communication hub is a cable television headend; and
at least one of the communication nodes is operable to provide cable television signals from the headend to a plurality of taps.

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